REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
5 June 1995

3. REPORT TYPE AND DATES COVERED
Final Report, 15 August 1993-30 April 1995

4. TITLE AND SUBTITLE
Research in Spread-Spectrum Radio Systems and Network

5. FUNDING NUMBERS
DAAH04-93-G-0253

6. AUTHOR(S)
Michael B. Pursley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wireless Communications Laboratory
102 Riggs Hall, Box 340915
Clemson University
Clemson, SC 29634-0915

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 32164.9-EL

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This is the final report for Grant DAAH04-93-G-0253 from the U.S. Army Research Office to Clemson University. Research on frequency-hop mobile radio communications is described. A list of publications is included, and contributions to technology transfer are listed.

14. SUBJECT TERMS
frequency-hop radio, tactical communications, error-control coding

15. NUMBER OF PAGES
5

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

FINAL REPORT

ARO PROPOSAL NUMBER: 32164–EL

PERIOD OF RESEARCH GRANT: 15 August 1993 — 30 April 1995

TITLE OF PROPOSAL: Research in Spread–Spectrum Radio Systems and Networks

GRANT NUMBER: DAAH04–93–G–0253

NAME OF INSTITUTION: Clemson University

AUTHOR OF REPORT: M. B. Pursley

SCIENTIFIC PERSONNEL SUPPORTED BY THIS GRANT

Professor M. B. Pursley
Research Associate/Asst. Professor D. L. Noneaker
Graduate Research Assistants J. H. Gass and J. M. Shea

LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD

[1] M. B. Pursley, "The derivation and use of side information in frequency-hop spread spectrum," *IEICE Transactions on Communications: Special Issue on Spread Spectrum Techniques and Applications*, vol. E76-B, pp. 814-824, August 1993.

[2] C. D. Frank and M. B. Pursley, "Concatenated coding alternatives for frequency-hop packet radio, " *IEICE Transactions on Communications: Special Issue on Spread Spectrum Techniques and Applications*, vol. E76-B, pp. 863-873, August 1993.

[3] C. D. Frank and M. B. Pursley, "Concatenated coding for frequency-hop spread-spectrum with partial-band interference," submitted to the *IEEE Transactions on Communications.*

[4] M. B. Pursley, "Reed-Solomon codes in frequency-hop communications," Chapter 8 of *Reed-Solomon Codes and their Applications*, IEEE Press, pp. 150-174, 1994.

[5] U. Madhow and M. B. Pursley, "Universal receivers with side information from the demodulators: An example for nonselective Rician fading channels," *IEEE Transactions on Communications*, vol. 42, pp. 2395-2405, July 1994.

[6] C. D. Frank and M. B. Pursley, "Concatenated coding for frequency-hop spread-spectrum with partial-band interference," accepted for publication in the *IEEE Transactions on Communications.*

[7] J. H. Gass, Jr., and M. B. Pursley, "Effects of correlated fading on frequency-hop communications with Reed-Solomon coding," *International Journal of Wireless Information Networks*, vol. 1, no. 3, pp. 177-186, 1994.

[8] U. Madhow and M. B. Pursley, "On the design of universal receivers for nonselective Rician fading channels," *IEEE Transactions on Communications*, vol. 42, no. 9, pp. 2703-2712, September 1994.

[9] U. Madhow and M. B. Pursley, "Mathematical modeling and performance analysis for a two-stage acquisition scheme for direct-sequence spread spectrum CDMA," accepted for publication in the *IEEE Transactions on Communications.*

[10] C. D. Frank and M. B. Pursley, "Error probability bounds for maximum-likelihood and reduced-state decoding of trellis codes on ISI channels," submitted for publication in the *IEEE Transactions on Information Theory.*

[11] C. W. Baum and M. B. Pursley, "Bayesian erasure techniques for frequency-hop spread-spectrum communications with fading and partial-band interference," *Proceedings of the Third IEEE International Symposium on Spread Spectrum Techniques and Applications*, (Oulu, Finland), vol. 1, pp. 238-242, July 1994.

[12] M. B. Pursley and J. M. Shea, "Soft-decision decoding for trellis coding and phase-difference modulation," accepted for presentation and publication in the *Proceedings of the 1995 IEEE International Symposium on Information Theory*, (Whistler, B.C., Canada), September 1995.

MOTIVATION FOR THE RESEARCH

In order to satisfy the need for increased information throughput in tactical radio systems and networks, it is beneficial to incorporate bandwidth efficient modulation and coding into future frequency-hop (FH) military radios. This permits the transmission of more information within the bandwidth allocated to a particular service, such as voice, data, or video. Bandwidth efficiency can also be improved by reducing the spacing between adjacent frequency slots.

As frequency slots are packed more closely, the correlation in the fading processes of different frequency slots can degrade performance significantly. In order to begin to design systems which perform well in spite of this correlation, it is necessary to obtain a method for the evaluation of the error probability for FH transmission over a frequency-selective fading channel. Such a method has been developed, and it has been applied to obtain performance curves for a range of correlation bandwidths for the fading channel.

Trellis-coded modulation offers increased spectral efficiency, and so it is a natural candidate for inclusion in future FH tactical radios. Because of the desire to use commercial off-the-shelf (COTS) equipment, pragmatic trellis codes are preferred, because they can be decoded with standard binary convolutional decoders.

Most forms of trellis-coded modulation that have been developed for telephone line modems are not appropriate for tactical mobile wireless networks. In particular, the quadrature-amplitude modulation (QAM) constellations are not consistent with efficient radio implementations because of the sensitivities of QAM signaling to gain variations in the channel and nonlinear amplification in the transmitter. Our research has dealt with multi-level phase modulation methods that permit nonlinear amplification and amplitude-robust demodulation. Also, the coherent demodulation methods employed in wireline modems are not suitable for mobile radio channels, because of the Doppler shifts introduced by vehicle motion and the oscillator phase instabilities in the radios themselves. Our research has focused on methods of modulation and demodulation that are tolerant of phase variations in the received signal.

SUMMARY OF RESEARCH FINDINGS

We have obtained several important results on concatenated coding scheme with both block and convolutional inner codes and Reed-Solomon outer codes, as described in [2] and [3]. Such codes provide good communication range and good anti-jam performance simultaneously. Various short block codes have been evaluated for use as inner codes, and concatenated coding has been compared with coding methods that use test symbols to obtain side information for erasures in the decoding of the Reed-Solomon code. Several comparisons are given in [1] and [4].

A convolutional or short block code is utilized within each dwell interval to detect errors and correct errors due primarily to "soft" interference. Interleaved Reed-Solomon outer codes are used to encode symbols across dwell intervals, and this code is principally responsible for correcting "hard" errors (e.g., due to strong partial-band jamming or hits from multiple-access interference).

During the reception of a message by a slow-frequency-hop (SFH) radio receiver, some fraction of the dwell intervals will have hard interference or both hard and soft interference, and some fraction will have soft interference only. Data in dwell intervals with soft interference only will, with reasonably high probability, be decoded correctly by the inner code. Typical inner codes are likely

to produce a burst of errors when they do not decode correctly, so the outer code must be able to correct burst errors due to decoding errors made by the inner code during periods of soft interference, as well as to correct errors due to hard interference. If hard interference is not present in too large a fraction of the dwell intervals, the outer code can correct these errors because of the interleaving structure and the capabilities of the code.

We have also investigated the effects of frequency-selective fading on the performance of SFH radio reception. All previous analyses of the performance of coding systems for SFH radios require that there be no statistical dependence between the fading that takes place in different frequency slots. However, if the fading process has a wide correlation bandwidth, the assumption of statistical independence is not valid. The transmission of FH spread-spectrum signals over a frequency-selective fading channel results in correlation among the amplitudes of the received signals, even if they are in different frequency slots. The correlation among the fade levels in different frequency bands in turn produces statistical dependence among symbols that are received in different frequency slots. Error-control coding performance can suffer from the dependent errors that are introduced by the correlated fading. In particular, the effectiveness of interleaving can be reduced significantly.

From the model of the fading process, we have deduced a model for the statistical dependence in the sequence of channel gains associated with the sequence of frequencies used by the frequency hopper. This model is then used to determine the performance of different coding techniques. For a FH system with 100 frequency slots, binary frequency-shift key modulation, noncoherent demodulation, a (32,12) Reed-Solomon error-correcting code, and a codeword error probability of 10^{-3}, our results show a degradation of a little more than 2 dB due to the correlated fading in a channel with a correlation bandwidth that is 20% of the width of the frequency slot. Further discussion and numerical result are presented in [7].

Phase-difference modulation, particularly M-ary differential phase-shift keying (M-DPSK) or M-ary double-differential phase-shift keying (M-D^2PSK), is well-suited to the requirements of mobile radio networks in which it is difficult to obtain an accurate phase reference. Either M-DPSK or M-D^2PSK may be coupled with trellis coding to decrease the probability of bit error for a given signal-to noise ratio. Standard hard-decision demodulation is easy to implement, but it does not provide information on the relative reliabilities of the bit decisions that result from a symbol decision. Because some bit decisions are more reliable than others, soft-decision demodulation and decoding should be employed.

We have developed a suboptimal method to generate quantized soft information for each bit associated with an M-PSK symbol. This method exploits the way bits are assigned to symbols in the M-PSK constellation, and it is simple to implement in the last stage of the demodulator. Results for the different channel configurations show that the proposed method provides a significant performance increase over hard-decision demodulation and decoding. Simulation results are presented to quantify the additional coding gain that is obtained from using soft decisions instead of hard decisions. We found that a simple two-bit quantization scheme for 8-DPSK with the rate 2/3 pragmatic trellis code provides more than 1.5 dB additional coding gain over the hard-decision system on the AWGN channel with a stable phase. More importantly, for the same system on an AWGN channel with a linear phase drift, the simple two-bit quantized soft-decision system with 8-DPSK performs up to 4 dB better than the hard-decision system

TECHNOLOGY TRANSFER

1) In this past year, our methods for development and use of side information in the decoder were incorporated into the SINCGARS System Improvement Program (SIP). Basic research results obtained by the PI and his colleagues and graduate students under ARO grants and contracts have been adopted for use in the SIP to provide enhanced performance in future SINCGARS radios. Mr. Jim McChesney of ITT has sent a letter to Dr. William Sander of ARO describing the transfer of these research results into SINCGARS SIP radio technology.

2) We continued collaboration with Techno-Sciences, Inc., and ITT Aerospace/ Communications Division on adaptive protocols for FH packet radio networks. We collaborated on new forwarding techniques that utilize multiple packets per transmission to obtain significant increase in throughput. Three Clemson faculty and three Clemson graduate students are working with Techno-Sciences and ITT on this project.

3) We completed a joint project with Techno-Sciences, Inc., and ITT Aerospace/ Communications Division on multi-function radio networks for Rome Laboratories. Several Clemson faculty participated in this project.

4) We started a project with ITT Aerospace/Communications Division and several other companies on the future digital radio technology for tactical wireless communications networks. This project encompasses the technology involved in the U.S. Army Future Data Radio and Near-Term Digital Radio programs at CECOM.

5) We participated in several activities in wireless communication systems and wireless information networks through the Wireless Communications Program and the Center for Computer Communication Systems at Clemson University.

7) We presented a briefing to Mr. Jim McChesney of ITT in December, 1994. Among the four graduate-student presentations was a presentation by graduate research assistant John Shea on the research results obtained to date on the use of trellis-coded modulation, differential demodulation, and soft decisions.

8) Clemson graduate student John Gass has be employed by ITT, and he has moved into an office at Clemson's Center for Applied Technology in Pendleton, SC, not far from the Clemson campus. John will continue his Ph.D. studies while working part time for ITT. His presence in the Center will facilitate even greater interaction between Clemson and ITT.

9) The Clemson-led team was selected to receive a grant under the DoD Focused Research Initiative. Some of the research described in this report will continue under the sponsorship of ARO as part of the FRI project.